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DOI:

[10.1016/j.mri.2016.03.017](https://doi.org/10.1016/j.mri.2016.03.017)

Document Version

Peer reviewed version

[Link to publication record in King's Research Portal](#)

Citation for published version (APA):

Letelier, K., Urbina, J., Andía, M., Tejos, C., Irarrazaval, P., Prieto, C., & Uribe, S. (2016). Accelerating dual cardiac phase images using undersampled radial phase encoding trajectories. *Magnetic resonance imaging*, 34(7), 1017-1025. [10.1016/j.mri.2016.03.017](https://doi.org/10.1016/j.mri.2016.03.017)

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Accelerating Dual Cardiac Phase Images Using Undersampled Radial Phase Encoding Trajectories

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“Informed consent was obtained from all individual participant included in the study”

ABSTRACT

A three-dimensional Dual-Cardiac-Phase (3D-DCP) scan has been proposed to acquire two data sets of the whole heart and great vessels during the end-diastolic and end-systolic cardiac phases in a single free-breathing scan. This method has shown accurate assessment of cardiac anatomy and function but is limited by long acquisition times.

This work proposes to accelerate the acquisition and reconstruction of 3D-DCP scans by exploiting redundant information of the outer k -space regions of both cardiac phases. This is achieved using a modified radial-phase-encoding trajectory and gridding reconstruction with uniform coil combination. The end-diastolic acquisition trajectory was angularly shifted with respect to the end-systolic phase. Initially, a fully-sampled 3D-DCP scan was acquired to determine the optimal percentage of the outer k -space data that can be combined between cardiac phases. Thereafter, prospectively undersampled data were reconstructed based on this percentage. As gold standard images, the undersampled data were also reconstructed using iterative SENSE. To validate the method, image quality assessments and a cardiac volume analysis were performed.

The proposed method was tested in thirteen healthy volunteers (30 y.o. mean age). Prospectively undersampled data (R=4) reconstructed with 50% combination led high quality images. There were no significant differences in the image quality and in the cardiac volume analysis between our method and iterative SENSE. In addition, the proposed approach reduced the reconstruction time from 40 minutes to 1 minute.

In conclusion, the proposed method obtains 3D-DCP scans with an image quality comparable to those reconstructed with iterative SENSE, and within a clinically acceptable reconstruction time.

Key words: whole-heart MRI, Dual Phase, view sharing, radial phase encoding.

1. INTRODUCTION

Assessment of cardiac anatomy and function using Magnetic Resonance (MR) imaging is still mainly based on the acquisition of multiple two dimensional (2D) cine images using balanced steady state free precession (b-SSFP) sequences [1]. This approach has several disadvantages, including the need of expertise to plan different views of the heart; the possibility of slice misalignment; and the need of several breath-holds, which makes it difficult to apply this approach in children.

Isotropic non-angulated three dimensional (3D) cardiac MR can overcome some of these problems since it requires minimal planning and the data can be reformatted in any plane [2]. For this purpose, different techniques have been proposed to study anatomy [3-5]; function [6] and flow of the whole heart and great vessels [7]. Among them, a sequence called 3D dual cardiac phase [8] allows assessment of the heart anatomy and evaluation of functional parameters from a single free breathing scan [8, 9]. This approach uses a 3D b-SSFP sequence, Cartesian sampling and SENSE reconstruction, typically with acceleration factors of two; however, the acquisition time still remains long.

In order to speed up the acquisition of static whole heart images, a Radial Phase Encoding (RPE) trajectory has been proposed [10]. RPE is a non-Cartesian acquisition trajectory that combines Cartesian readouts and radial phase encoding steps. The images from RPE trajectories are usually reconstructed using iterative SENSE. This technique uses additional information from coil sensitivity maps to remove undersampling artifacts [11, 12].

For dynamic MRI, the redundant information between images has been used to speed up the acquisition of the MR data [13-15]. The most common approaches are k -t methods [16] and compressed sensing methods [17, 18]. Another method that combines k -space data between images acquired at different time points is key-hole [14, 15]. This approach continuously collects low frequencies from k -space and acquires high k -space frequencies only once. These high frequencies are then used to fill the high frequencies that were not acquired during other time points. An alternative method, based on a golden ratio RPE scan, has been recently proposed to exploit redundant information and to speed up the acquisition of dynamic contrast enhanced MRI [12]. This method takes advantage of the RPE trajectory that oversamples the center of k -space, and continuously updates low frequencies, similar to key-hole approaches. However, in contrast to key-hole, high frequencies are also acquired at each time frame. In this approach, it is important to know the amount of k -space information that can be shared between different time points [19].

In this work, we propose a new technique that combines k -space data from two different RPE trajectories to accelerate the acquisition of the 3D dual cardiac phase sequence. This approach is based on the use of complementary and undersampled RPE trajectories for each cardiac phase. Our main hypothesis is that the outer k -space information can be combined between both cardiac phases, allowing the use of a simple multiple-coil gridding reconstruction to obtain artifact-free images with similar quality as those provided by iterative SENSE, but with a reduced reconstruction time.

2. METHODS

Acquisition scheme

A 3D Dual Cardiac Phase scan with a RPE acquisition trajectory was implemented. The RPE trajectories for end-systole and end-diastole were angularly shifted with respect to each other (Fig. 1). The angular shift was equal to half of the angular step used in each RPE trajectory.

To speed up the acquisition, the RPE trajectories were undersampled in the angular (R_a) and radial (R_r) directions in a similar fashion as proposed in [10]. The undersampling along the radial direction was performed using an interleaved undersampling scheme, such that the sampled locations were shifted in the

radial direction by one position from one angular direction to the next one. The total acceleration was the product of both factors: $R=R_a \cdot R_r$. We defined the RPE trajectory as fully sampled when the number of k -space encodings was identical to a Cartesian trajectory for the same spatial resolution.

The proposed acquisition scheme was implemented on a 1.5T Achieva Clinical MR scanner (Philips Healthcare, Best, NL).

Reconstruction methods

Since RPE trajectories for end-systole and end-diastole were angularly shifted with respect to each other, it was possible to combine k -space data between both cardiac phases. If 60% of the data was shared, it meant that 60% of the outermost k -space points from one cardiac phase were added to the other cardiac phase and vice versa as shown in Fig. 1.

After k -space data were combined, a Fourier transform was applied along the readout direction. Then, for each readout point, the phase encoding steps remained distributed on a radial trajectory. Data were reconstructed using gridding with uniform coil combination as proposed by Roemer et al. [20]. For comparison purposes, we reconstructed the original data, i.e. without combining k -space information between cardiac phases, using non-Cartesian iterative SENSE. The stopping criterion of the iterative method was that the residual needed to be lower than 10^{-3} or reach a maximum of eight iterations.

For gridding and non-Cartesian iterative SENSE reconstruction, we used the following density compensation function:

$$DCF(K_y, K_z) = \begin{cases} \left(\sqrt{K_y^2 + K_z^2} \right)^{-1} < Kr \\ 2 * \left(\sqrt{K_y^2 + K_z^2} \right)^{-1} \geq Kr \end{cases} \quad \text{Eq. 2}$$

where K_y and K_z correspond to both phase encoding directions, K_r is the ratio of areas in k -space that defines the area between those points which were and were not shared between different cardiac phases.

Experiments

1D simulation

Two simulations were performed to analyze the effect of combining outer k -space information from two data sets. The first simulation evaluated the level of blurring introduced by the proposed method (Fig. 2, a to f). The second simulation evaluated the definition of the edges when combining profiles from different simulated cardiac phases (Fig. 2 g to l).

For both simulations, different pairs of 1D k -space profiles with different waveforms, centers and widths were generated. Each profile simulated an image acquired at end-systole or at end-diastole. The following function was used to simulate the profiles:

$$y(k) = \exp\left(-\left(\frac{k-d}{w}\right)^c\right) \quad \text{Eq.3}$$

where d represents the center of the profile, w represents the width and c is a parameter that controls the shape of the profile. As c increases, the Fourier transform of the profile starts to resemble a rect function.

To simulate the proposed acquisition and reconstruction approach, the k -space data of each profile was combined as follows. For each pair, certain percentage of the outer k -space of one profile was inserted in an interleaved fashion into the other profile. However, the inner k -space for each profile remained the same.

For the first simulation, two profiles were combined at 100, 99%, 90%, 50% and 25% of the outer k -space data and then reconstructed. For the second simulation, 50% of the outer k -space was combined in three different pairs of profiles. Two of these three pairs, had the same waveform, but in each pair, one profile had a 50% width change and 10% center change with respect to the other profile. In the third pair, one profile had a different waveform, center and width respect to the other profile. These changes were made in order to simulate different cardiac phases.

In vivo experiments

After imaging localizers and a SENSE reference scan, a 2D b-SSFP cine free-breathing image of the long horizontal axis of the heart with high temporal resolution (spatial resolution = $1 \times 1 \times 8$ mm and 50 cardiac phases) was acquired to determine the quiescent period of the heart at end-systole and end-diastole. Subsequently, end-systolic and end-diastolic images with prospective ECG-gating and arrhythmia rejection using the dual cardiac phase scan with the proposed shifted RPE scheme were acquired in thirteen healthy volunteers (30 y.o. mean age, with a median of 26 y.o., 11 men) using a 5-element cardiac coil. Acquisition parameters for the dual cardiac phase scan included: b-SSFP sequence, flip angle=90°, TR/TE=4.1ms/2.0ms, FOV of $384 \times 288 \times 288$. In addition, a fat-saturation and a T2-preparation pulse (four 180° pulses and TE of 35ms) were employed to null fat signal and to improve myocardial blood pool contrast [21]. Furthermore, the acquisitions were performed during free breathing using a navigator echo with a respiratory navigator window of 6 mm and ECG trigger. All images were reconstructed using a matrix size of $192 \times 144 \times 144$, leading to an isotropic reconstructed voxel size of $2 \times 2 \times 2$ mm. The local ethics committee approved the study and all volunteers provided written informed consent.

Retrospective undersampled acquisition

In four of the thirteen volunteers, fully sampled data sets were acquired using the proposed 3D Dual Cardiac Phase RPE acquisition. These data sets were retrospectively undersampled to determine the amount of outer k -space information that can be combined between both cardiac phases. The fully sampled RPE data sets were retrospectively undersampled as described above. The undersampling factors were $R_r=2$ and $R_a=2$, so the final undersampling factor was $R=4$. Thereafter, end-systolic and end-diastolic images were reconstructed by sharing outer k -space data for different percentages from 0 to 100%, in 10% increments. All data sets were reconstructed using gridding with uniform coil combination. As a gold standard, the fully sampled RPE data sets were also reconstructed using iterative SENSE.

The Root Mean Squared (RMS) error between the fully sampled iterative SENSE image and the proposed reconstruction of retrospectively undersampled data was computed. The percentage of k -space to be combined between both phases was determined from this analysis. The RMS error was estimated in a Region of Interest (ROI) that included the entire heart and the great vessels.

Prospective undersampled acquisition

In nine of the thirteen volunteers, prospective undersampled k -space data were acquired with undersampling factors of $R_r=2$ and $R_a=1$ and 2, which resulted in final undersampling factors of $R=2$ and 4. K -space data acquired with $R=4$ was then combined using a specific percentage of k -space determined from the fully sampled RPE acquisitions, and reconstructed using the proposed approach. For comparison, the

purely undersampled data, for $R=2$ and 4 were reconstructed using iterative SENSE. The data set with undersampled factor $R=2$ was reconstructed with iterative SENSE as a gold standard.

Image quality assessment and statistical analysis

Three tests were performed to assess the quality of the images provided by the proposed method. The first test was performed to evaluate image quality in terms of edge definition and artifact level. Image scores ranged between one (edges not defined), two (edges poorly defined), three (edges well defined) and four points (excellent edge definition). A similar score was used to define artifact level. This test was performed by two blinded observers (S.U. and M.A.) with 9 and 5 years of experience in cardiac MRI. A Wilcoxon signed rank test was used to compare image quality between the proposed approach and iterative SENSE.

For the second test two images acquired with the same undersampling factor were shown simultaneously to two blinded observers (S.U. and C.P. with 9 and 7 years of experience in cardiac MR). One image was reconstructed with the proposed approach and one with iterative SENSE, and the observers were asked to answer which image had better image quality, or if they had the same image quality. A one-proportion z-test was performed to compare the methods.

The first and second tests to compare the proposed method and iterative SENSE were performed in an axial image at medium level of the left ventricle and between the proposed approach and iterative SENSE reconstruction.

The third test was performed to assess cardiac volumes. This test was performed in images acquired with an undersampling factor of $R=4$, reconstructed with both the proposed method and iterative SENSE. Additionally, cardiac volumes were also analyzed in gold-standard images reconstructed with iterative SENSE for $R=2$. In all cases end-systolic, end-diastolic and stroke volumes were calculated on images reformatted along the short axis view (Osirix v.5.7.1). A trained person blinded to the imaging data delineated the epicardial contours of the left ventricle; papillary muscles were included in all measurements. A paired t-test was performed to check if there was any statistically significant difference between the cardiac volumes obtained from the proposed method, iterative SENSE and the gold standard technique. Additionally, an ANOVA test was used to compare the volumes obtained from the proposed approach, with different undersampling factors, and iterative SENSE. Finally, Bland Altman plots were created to assess consistency between the proposed method and iterative SENSE.

3. RESULTS

1D Simulation

Results of the first simulation are shown in Fig. 2 (a – f). We observed that the edges of the profiles are blurred when the combination of the outer k -space corresponded to 100% and 99% of the length of the profiles. For a 90% combination, a small distortion can be observed in the plateau of the profile, while the edges are negligibly blurred. When the outer k -space combined was 50% or lower of the length of the profile, no differences were observed between the combined and the original profile.

Fig. 2 (g - l) shows the original profile pairs and the result after they were combined using 50% of the outer k -space. When the combination strategy involved profiles with abrupt edges, some artifacts appeared at the edges of the other profile (Fig. 2 g - h). However, for profiles with less abrupt edges (Fig. 2 i - l), there were not visual differences between the original and combined profiles, even when the waveform had different shapes (Fig. 2 k - l).

In vivo-experiments

The averaged heart rate of volunteers was 65 beats per minute. The nominal acquisition time for each sequence was 13:45 minutes for fully sampled images, 6:51 minutes for R=2 and 3:24 minutes for R=4. The mean reconstruction time for a data of two cardiac phases with an undersampling factor of 4 using a standard CPU (Intel Core i7, CPU 3.40 GHz and RAM 32 GB) running a Matlab code (Matlab 2009b, Mathworks) was 1 minute for the proposed method and 40 minutes for non-Cartesian iterative SENSE.

Retrospective undersampled acquisition

End-systolic and end-diastolic images reconstructed with the proposed approach for different percentage of k -space data combinations are depicted in Fig. 3. Image quality improved as the percentage of combination increased. Although the method typically reduced undersampling artifacts, for high percentage of outer k -space combination, noise and artifact level increased. The RMS error analysis between the fully sampled RPE data reconstructed with iterative SENSE and the proposed method decreased until the k -space combination was 40-60% between end-systole and end-diastole. For percentages of outer k -space combination higher than 60%, the RMS error increased.

Prospective undersampled acquisition

An example of undersampled images reconstructed using iterative SENSE and the proposed approach are shown in Fig. 4 for undersampling factor R=4. The obtained images were, in general, similar between the reconstruction techniques. Minimal artifacts can be appreciated in the images reconstructed with iterative SENSE.

Image quality assessment and statistical analysis

The results of the first image quality analysis are shown in Fig. 5 and Table 1. As expected, the highest scores were obtained for the iterative SENSE reconstruction image acquired with R=2, which was considered as the gold standard. Regarding edge definition, for an undersampling factor R=4, 77.8% of the images had an image quality greater than or equal to 3 using iterative SENSE, compared to 94.5% and 100% in the proposed approach for end-systole and end-diastole, respectively. Considering artifact level, 83.3% and 83.4% of the images had an image quality better than or equal to 3 using iterative SENSE for end-systole and end-diastole respectively, and 77.7% and 83.3% using the proposed approach.

The Wilcoxon Signed Rank test to compare the median values of edge definition and artifact level showed that the undersampled acquisitions (R=4) were statistically different from the gold standard (iterative SENSE R=2) independently of the reconstruction method, except in two cases. We did not find statistically significant differences between the gold standard and iterative SENSE (R=4) for edge definition in the end-systolic images ($p = 0.059$) and for artifact level in the end-diastolic images ($p = 0.059$). We also found no statistically significant differences between images acquired with the same undersampled factor (R= 4) between the proposed approach and iterative SENSE for all cases (edges definition and artifact level for both cardiac phases).

Results of the second image quality test showed that for an undersampling factor R=4, the proposed approach had equal or better image quality than the images obtained using the iterative SENSE (R=4) algorithm in 83% of the cases ($p = 0.91$).

Fig. 6 shows Bland Altman plots and the results of paired t-test student of the cardiac volume analysis. Bland Altman plots showed a mean difference close to 0 when comparing any of the methods. However, the

standard deviation was much lower when comparing our method with the gold standard (± 0.89) than when comparing iterative SENSE ($R=4$) with the gold standard (± 2.45). The paired t-test student between the gold standard (iterative SENSE $R=2$) and the proposed approach ($R=4$) did not show statistically significant differences for any of the functional parameters (EDV, $p=0.34$; ESV $p=0.64$; and SV $p=0.93$). When comparing the gold standard with iterative SENSE reconstruction ($R=4$), we also did not find statistical differences for the EDV ($p=0.15$), ESV ($p=0.17$) and SV ($p=0.20$). Additionally, results of the one-way ANOVA test between all volumetric data sets showed no statistical differences for all parameters (EDV, $p=0.47$; ESV $p=0.85$; and SV $p=0.99$).

4. DISCUSSION

We have proposed a new approach that obtains images from the dual cardiac phase scan with excellent image quality using undersampled RPE trajectories. Furthermore, combining k -space data with a uniform coil combination reduced the reconstruction time from 40 minutes using iterative SENSE to 1 minute for the two 3D data sets using the proposed method.

Our acquisition and reconstruction approach takes advantages of the fact that the center of the k -space is oversampled and maintained for each cardiac phase and only combines the undersampled regions of outer k -space. This characteristic of the RPE trajectory improves the image quality in comparison to traditional 2D radial trajectories. 2D radial trajectories for view sharing reconstruction often results in images with blurred edges because information of low frequencies and high frequencies are combined from different time points. In our case, the RPE trajectories allowed us to avoid combination of the low frequencies to achieve images with good edge definition.

We tested our reconstruction strategy by simulating different profiles and combining different amounts of k -space. We showed that if only the outer k -space data is combined, negligible differences between the original and combined profiles are obtained. Differences were observed in profiles with abrupt edges. In cardiac MR images, such abrupt edges remain difficult to identify due to limited spatial resolution.

We proposed to reconstruct the combined data using gridding with uniform coil combination since it is a simple and efficient way to reconstruct non-Cartesian k -space, coil by coil. Gridding can generate artifacts when it is used to reconstruct undersampling k -space data. However, adding information from one cardiac phase to the other resulted in a significant reduction of those artifacts. On the other hand, iterative SENSE takes advantage of the additional information present in the multiple receiver coils. With multiple iterations, SENSE can find an optimized reconstructed image with the knowledge of the coil sensitivity maps, but requires several time-consuming iterations.

We defined the RPE trajectory as fully sampled when the number of k -space encoding was identical to a Cartesian trajectory for the same spatial resolution. Nevertheless, for radial trajectories, this definition still may violate the Nyquist criteria in the outer k -space. Therefore, the fully sampled RPE were reconstructed with iterative SENSE to avoid possible artifact due to radial undersampling.

The proposed method was validated using three different tests. The first image quality test showed that the proposed approach achieved similar or better image quality scores than iterative SENSE for the same acceleration factor ($R=4$). The second test, showed that images reconstructed with the proposed method achieved equal or better image quality than iterative SENSE for $R=4$ when they were compared at the same time. The third test showed that there were not statistically significant differences between cardiac volumes evaluated with any of the methods compared.

Limitations of the study

We acquired and reconstructed the images using a 5-element cardiac coil, however using a coil with more elements might allow the iterative SENSE method to achieve higher undersampling factors or better image quality. In this work we only used an undersampling factor of $R=4$. However, it has been shown that an undersampling factor as high as 8 can be achieved for RPE with iterative SENSE by using 32 channels while maintaining a clinically acceptable image quality [10]. We also expect that the proposed method could provide a better image quality increasing the number of coil elements; however, the acceleration factor achieved by our method does not necessarily depend on the same way with the number of receive coils.

Another limitation of the proposed study is that a multi-slice, multi-breathhold technique for assessing cardiac volumes was not included. This was mainly due to the length of the protocol. Nevertheless, it has been previously shown that the dual cardiac phase technique provides accurate cardiac volume assessment in adult [8] and pediatric patients with congenital heart diseases [22].

In conclusion, we have proposed a new method to acquire and reconstruct dual cardiac phase images combining k -space data from complementary RPE trajectories. The method achieved excellent image quality that allows a quantitative and qualitative assessment of the entire heart in a clinically reasonable scan and reconstruction time.

5. COMPLIANCE AND ETHICAL STANDARDS

Funding: This study was funded by project grant FONDECYT N°11100427 and N°1141036.

Conflict of interest: Author Karis Letelier declares that she has no conflict of interest. Author Marcelo Andia declares that he has no conflict of interest. Author Cristian Tejos declares that he has no conflict of interest. Author Pablo Irarrazaval declares that he has no conflict of interest. Author Claudia Prieto declares that she has no conflict of interest. Author Sergio Uribe declares that he has no conflict of interest.

Ethical approval: All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent: Informed consent was obtained from all individual participants included in the study.

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TABLES

	Edge Definition				Artifact Level			
	End-systole		End-diastole		End-systole		End-diastole	
	Median	Range	Median	Range	Median	Range	Median	Range
SENSE R=2	4	4-3	4	4-2	4	4-2	4	4-3
SENSE R=4	3	4-2	3	4-2	3	4-2	3	4-2
Proposed Approach R=4	3	4-2	3	4-3	3	4-2	3	4-2

Table 1. Scores for image quality assessment. Image scores ranged between one (edges not defined), two (edges almost defined), three (edges defined) and four points (excellent edges definition). A similar score was used to define artifact level. There were minor differences between SENSE R=4 and the proposed approach.

FIGURES

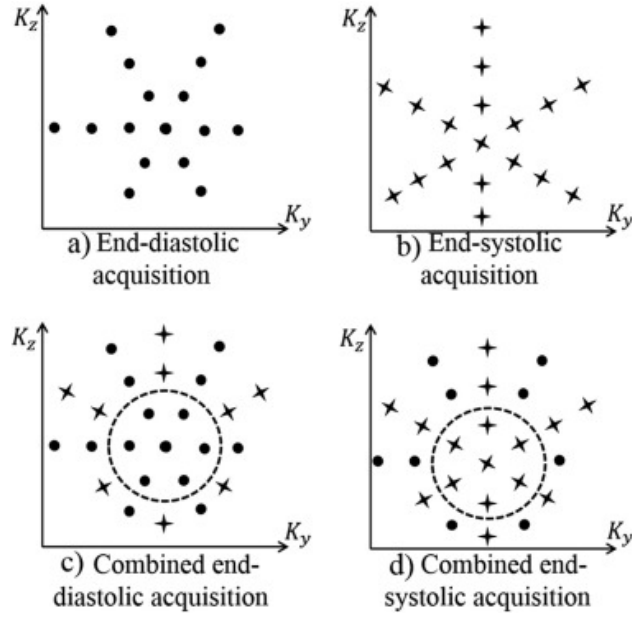


Fig. 1 a) and b) show the acquisition scheme of the RPE trajectory in one representative K_y - K_z plane of each cardiac phase, end-systole (black points) and end-diastole (black stars). c) and d) show the combined acquisition schemes for end-diastole and end-systole where the circle corresponds to the limit (K_r) of those points which are and are not shared between different cardiac phases.

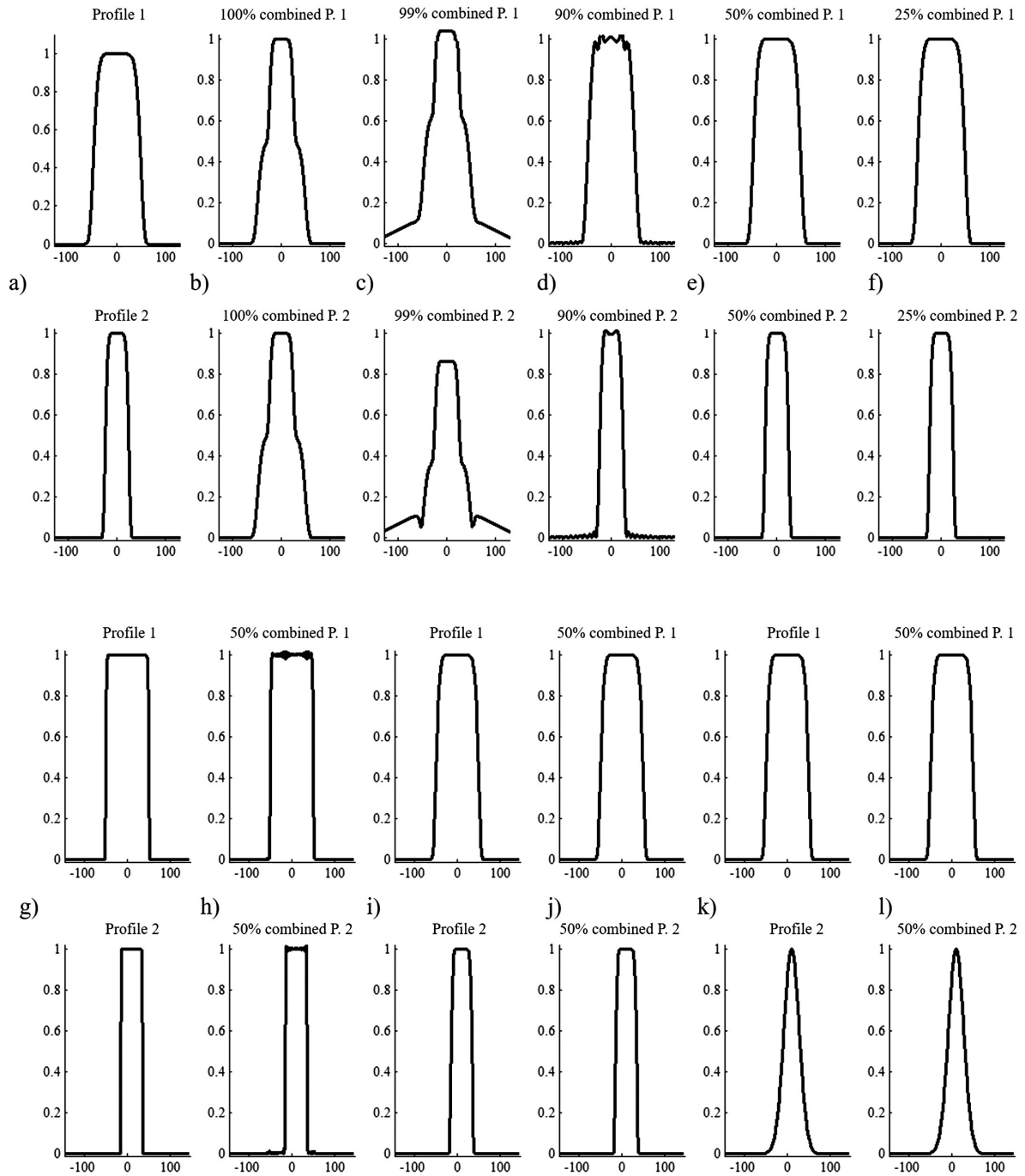


Fig. 2 Numerical simulations, the two initial profiles (a) are combined in different percentages 100%, 99%, 90%, 50% and 25% (from b to f). We observed that as the combined percentage decreases blurring decreases. We observed that for 50% or lower combination, no difference can be observed between the original and combined profile. Figure parts g), i) and k) shows the initial pair profile while the figure parts h), j) and l) shows a 50% combined profiles. In g), the profiles have abrupt edges, which result in visible artifact in the combined profile (h), whereas the profiles i) and k) had less abrupt edges, which resulted in negligible differences between the original and combined profiles (j and l), even when the combined profiles had different shapes (k).

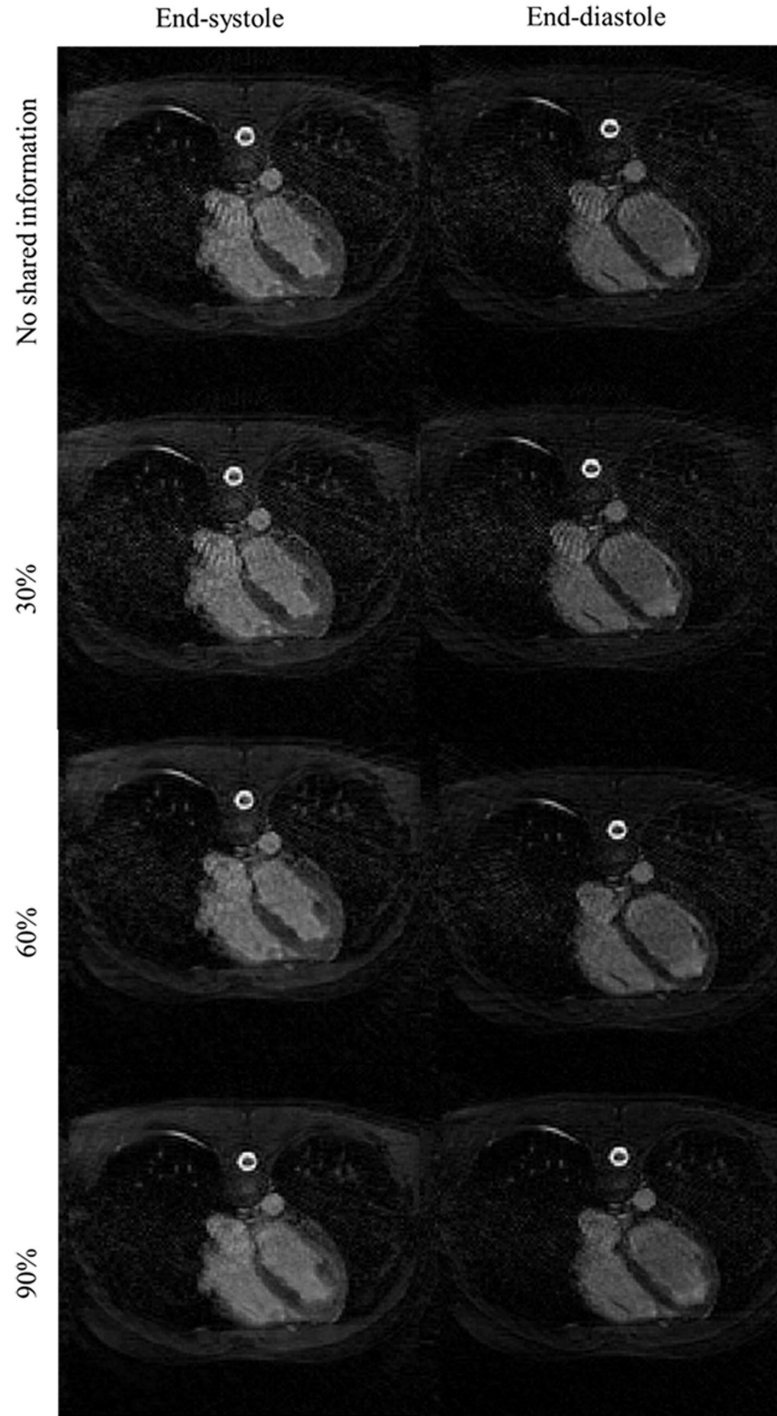


Fig. 3 End-systolic and end-diastolic images reconstructed with the proposed approach for different percentages of k -space data combinations with undersampled factor $R=4$. In the image with 60% of k -space samples shared, noise level and artifacts are minimal for the images presented. The RMSE value was 3.6, 3.2 and 3.8 for the combinations of 30%, 60 and 90% respectively when the images were compared against the gold standard.

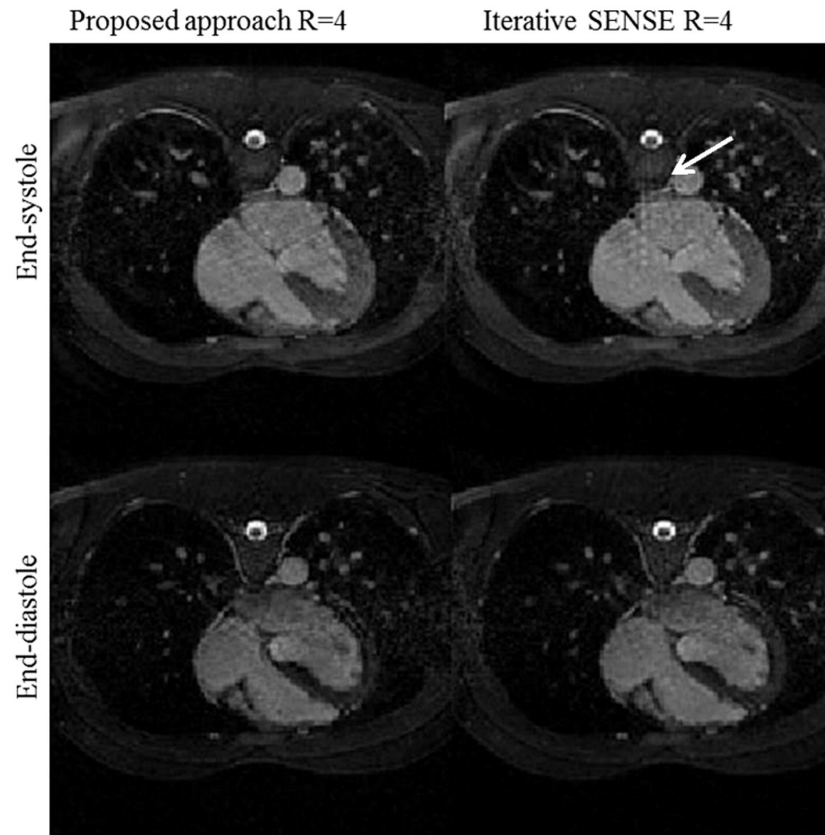


Fig. 4 End-systolic and end-diastolic images obtained with undersampling factor of 4. The first column shows the combined images reconstructed with gridding and uniform coil combination. The second column shows the undersampled images reconstructed with non-Cartesian iterative SENSE. End-systolic and end-diastolic images are shown in the superior and bottom rows, respectively. Although the obtained images are similar, a reduction of artifact can be appreciated using the proposed approach compared with the iterative SENSE reconstruction.

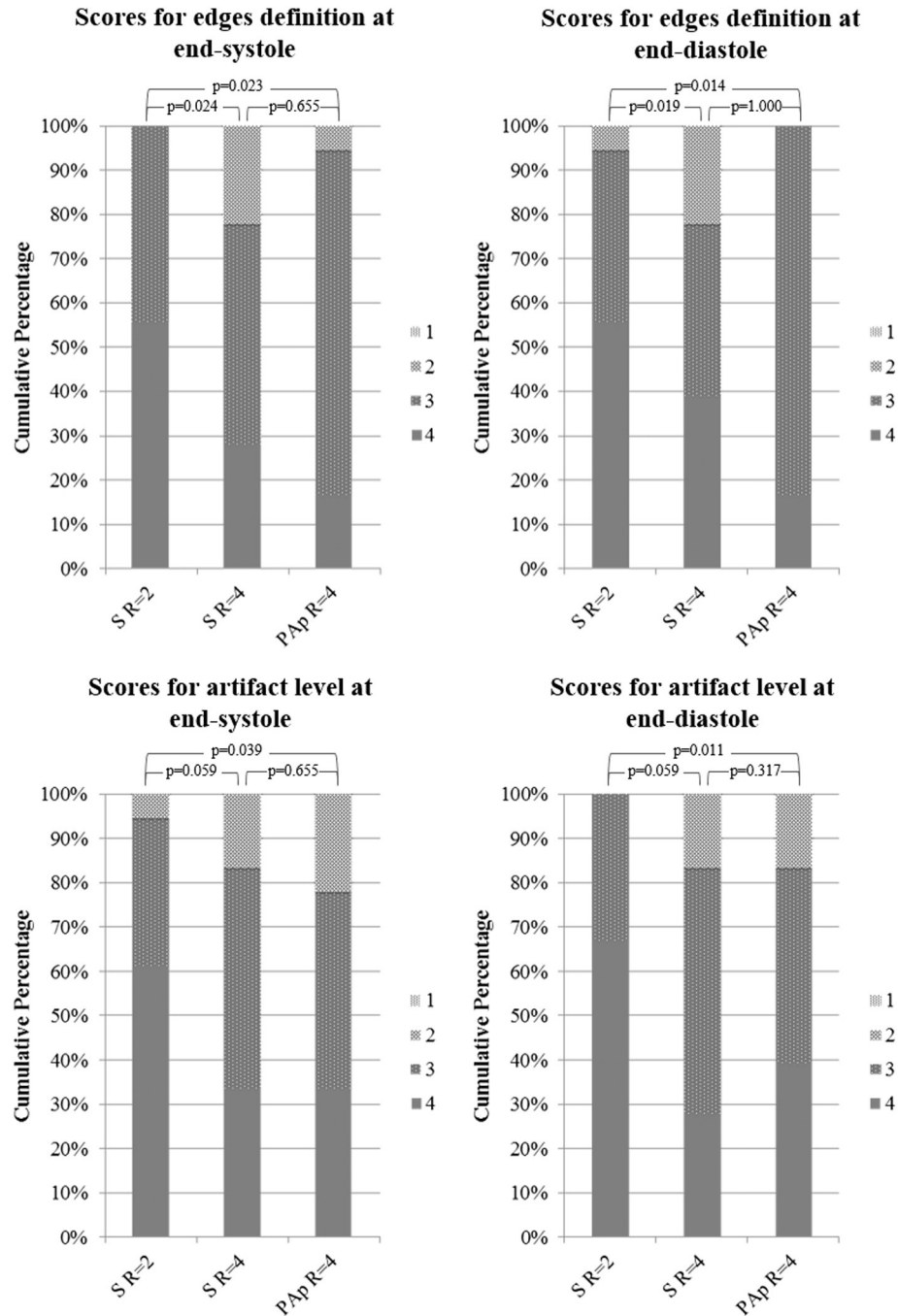


Fig. 5 Cumulative percentage of image scoring for each reconstruction method with different undersampling factor considering edges definition and artifact level. “S R=2” = SENSE reconstruction R=2, “S R=4” = SENSE reconstruction R=4, “PAp R=4” = Proposed Approach R=4. Results of the Wilcoxon signed rank test. No differences in the median can be observed between iterative SENSE and the proposed approach for the same undersampled factor (R=4).

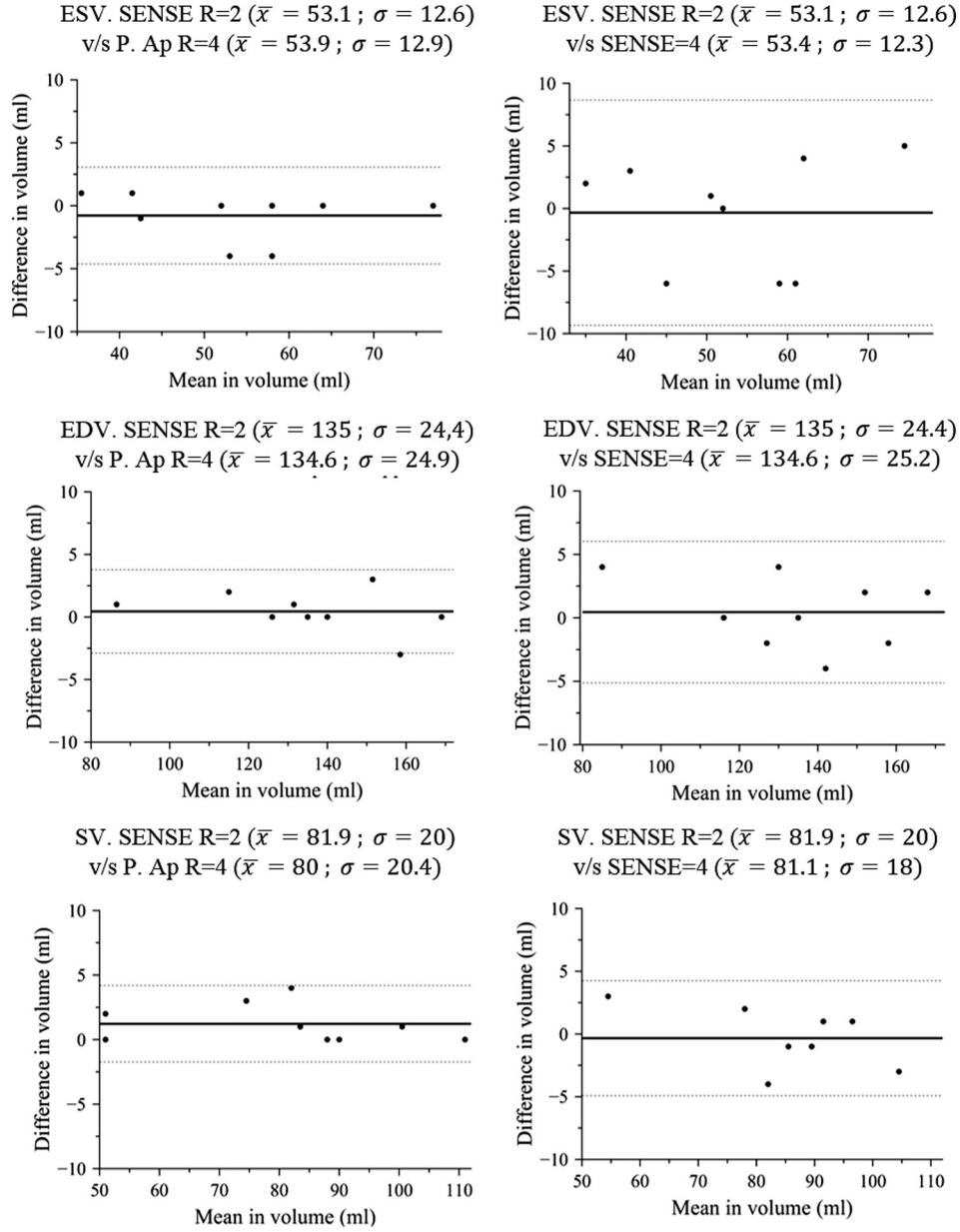


Fig. 6 Bland Altman plots and the results of paired t-test student of the cardiac volume analysis. Bland-Altman plots used to compare the quantification of cardiac volumes from images obtained using iterative SENSE reconstruction (R=2) with images obtained with the proposed approach and with iterative SENSE for R=4. Middle line=mean, upper and lower lines=2 standard deviations. Mean values and standard deviations of ESV, EDV and SV obtained from each technique are given in milliliters in the title of each figure part. ESV=End-Systole Volume, EDV = End-Diastole Volume and SV = Stroke Volume.